

Contents

1 Power supply systems	31
1.1 Functions of traction power supply	31
1.2 Traction power supply networks	31
1.2.1 Types of traction power supply systems	31
1.2.2 Basic structure of the traction power supply	35
1.2.2.1 Traction power generation	35
1.2.2.2 Traction power distribution	36
1.2.3 Direct current traction networks	38
1.2.4 AC 16,7 Hz single-phase traction networks	38
1.2.4.1 Traction power generation	38
1.2.4.2 Types of 16,7 Hz traction power networks	40
1.2.5 50 Hz single-phase AC traction networks	42
1.2.5.1 Power supply with single phase AC 50 Hz	42
1.2.5.2 Power supply with two phase AC 50 Hz	43
1.2.5.3 Advantages and disadvantages of power supply with single and double phase AC 50 Hz	44
1.3 16,7 Hz traction power supply of the German Railway	45
1.3.1 Energy generation	45
1.3.2 Energy transmission and contact line supply	45
1.3.3 Standard 16,7 Hz substations of the German Railway	46
1.3.3.1 Function and types of standard substations	46
1.3.3.2 110 kV open air equipment	47
1.3.3.3 15 kV indoor equipment	51
1.3.3.4 Auxiliaries' supply	53
1.3.3.5 Protection	54
1.3.3.6 Supervisory control and data acquisition system	56
1.3.3.7 Buildings and supporting structures	58
1.3.4 Power system control	59
1.3.4.1 Development, functions and design	59
1.3.4.2 Local control units and remote control lines	60
1.3.4.3 Remote control technology of the SCADA	62
1.3.4.4 Converters, remote control nodes and satellite control centres	63
1.3.4.5 Master control centres	63
1.3.4.6 Transmission control and network command centres	64
1.4 AC 25 kV 50 Hz traction power supply of the Madrid-Seville line	64
1.4.1 Line supply and connection	64
1.4.2 Substations and their components	66
1.5 DC 750 V traction power supply of the Light Rail Transit System LRT Ankaray	67

1.5.1	Line supply and switching	67
1.5.2	Substations and components	68
1.6	References	70
2	Requirements and specifications	73
2.1	General requirements	73
2.1.1	Introduction	73
2.1.2	Mechanical Requirements	74
2.1.3	Electrical requirements	74
2.1.4	Environmental requirements	75
2.1.5	Requirements due to interoperability	75
2.1.6	Requirements on expenditure	77
2.2	Requirements resulting from operation and line parameters	78
2.2.1	Introduction	78
2.2.2	Operating requirements	78
2.2.2.1	Long-distance main-line traffic	78
2.2.2.2	Local-area traffic	79
2.2.3	Requirements due to track-related factors	81
2.2.3.1	Long-distance main-line traffic	81
2.2.3.2	Urban and local-area traffic	82
2.2.4	Requirements due to the railway line location	82
2.2.4.1	Long-distance main line traffic	82
2.2.4.2	Local-area traffic	84
2.2.5	Clearance gauge related requirements	84
2.2.5.1	Long distance main-line traffic	84
2.2.5.2	Local-area traffic	91
2.3	Climatic conditions	93
2.3.1	Temperatures	93
2.3.2	Wind velocities and wind loads	95
2.3.3	Ice accumulation	96
2.3.4	Active substances in the air	96
2.3.5	Lightning voltage surges	96
2.4	Specifications due to pantographs	98
2.4.1	Design and functions	98
2.4.2	Properties of collector strips	98
2.4.3	Contact forces between the pantograph and the overhead contact line .	102
2.4.3.1	Basics for static contact force	102
2.4.3.2	Aerodynamic contact force	103
2.4.3.3	Dynamic contact force	104
2.5	Specifications on reliability and safety	106
2.5.1	Standards	106
2.5.2	Loading and strength	106
2.5.3	Hazards due to electricity	106
2.5.4	Insulation co-ordination	107

2.5.5	Protection against electric shocks	109
2.5.5.1	General protection against electric shocks	109
2.5.5.2	Protection against electric shocks by direct contact	110
2.5.5.3	Protection against electric shocks by indirect contact	111
2.5.5.4	Protection against electric shocks caused by the track potential	113
2.6	Environmental compatibility	113
2.6.1	General	113
2.6.2	Environmental relevance of electric traction	113
2.6.3	Land usage	114
2.6.4	Nature and bird protection	115
2.6.5	Aesthetics	115
2.6.6	Electric and magnetic fields	116
2.7	Physical characteristics of materials in contact line installations	117
2.8	References	118
3	Description of systems	123
3.1	Definitions	123
3.2	Overhead contact lines	125
3.2.1	Basic characteristics	125
3.2.2	Wires and stranded conductors	126
3.2.2.1	Contact wires	126
3.2.2.2	Steel wires	128
3.2.2.3	Stranded conductors	128
3.2.2.4	Synthetic ropes	129
3.2.3	Trolley-type contact lines	130
3.2.3.1	Definition and application	130
3.2.3.2	Single-point suspension with fixed anchored contact wire	130
3.2.3.3	Pendant-type suspension with and without automatic tensioning	130
3.2.3.4	Bridle-type suspension	131
3.2.3.5	Elastic supports	132
3.2.4	Trolley-type contact line with stitch suspension	132
3.2.5	Overhead contact lines with catenary suspension	133
3.2.5.1	Basic design	133
3.2.5.2	Contact lines with droppers at the supports	133
3.2.5.3	Contact lines with offset support droppers	133
3.2.5.4	Contact line with stitch suspension	134
3.2.5.5	Contact lines with inclined suspension	135
3.2.5.6	Contact lines with elastic dropper elements	137
3.2.5.7	Contact lines with auxiliary catenary wire, compound contact line	137
3.2.6	Horizontal catenary overhead contact lines	138
3.3	Conductor rails	139
3.3.1	Third rail installations	139
3.3.2	Types of conductor rail	140
3.3.3	Construction and operation of conductor rail installations	142

3.4	Overhead conductor rail installations	144
3.5	References	149
4	Contact line design, cross-span equipment, components and examples	151
4.1	Overhead contact lines	151
4.1.1	Basic design	151
4.1.2	Selection of the overhead contact line design	153
4.1.3	Selection of conductor cross sections and tensile forces	153
4.1.4	Selection of span lengths	156
4.1.5	Selection of system height	157
4.1.6	Design of contact lines in tunnels	157
4.1.7	Adoption of contact wire pre-sag	158
4.1.8	Selection of dropper spacing	158
4.1.9	Use of a stitch wire	159
4.1.10	Selection of tensioning section length	161
4.1.11	Design of connected and isolated overlaps	163
4.1.12	Design of overhead contact lines and their components	167
4.1.12.1	Configuration of overhead contact lines	167
4.1.12.2	Mechanical mid points	167
4.1.12.3	Automatic flexible tensioning	168
4.1.12.4	Fixed terminations	173
4.1.12.5	Droppers	173
4.1.12.6	Electrical connections	175
4.1.12.7	Electrical sectioning	175
4.1.12.8	Sectioning devices	175
4.1.12.9	Design of neutral sections and phase separations	177
4.2	Cross-span equipment	180
4.2.1	Introduction	180
4.2.2	Hinged cantilevers	180
4.2.3	Cantilevers across several tracks	184
4.2.4	Head-spans	184
4.2.4.1	Application	184
4.2.4.2	Design principles	185
4.2.4.3	Detailed structural design	186
4.2.5	Portal structures	187
4.2.6	Contact line pull-offs	188
4.2.7	Cross-span equipment in tunnels	188
4.3	Traction power lines	189
4.3.1	Definitions	189
4.3.2	Routing and support of traction power lines	191
4.4	Signals for electric traction	192
4.5	Guards to prevent accidental contact	193
4.6	Components and elements	194

4.6.1	General requirements	194
4.6.2	Overhead line disconnectors	194
4.6.3	Insulators	196
4.6.3.1	Purpose and loadings	196
4.6.3.2	Insulating materials	196
4.6.3.3	Designs and applications	197
4.6.3.4	Electrical and mechanical rating	198
4.6.3.5	Selection and application	199
4.6.4	Clamps and connecting fittings	201
4.6.4.1	Purpose	201
4.6.4.2	Mechanical and electrical rating	201
4.6.4.3	Materials	203
4.6.5	Electrical connections	204
4.6.6	Supporting assemblies	206
4.6.6.1	Requirements	206
4.6.6.2	Hinged tubular cantilever	207
4.6.6.3	Head span structures	210
4.6.7	Protection devices	212
4.7	Testing of components	213
4.7.1	Introduction	213
4.7.2	Clamps and connecting fittings	214
4.7.2.1	Type test	214
4.7.2.2	Random sample test	217
4.7.2.3	Routine test	219
4.7.3	Contact wires and other conductors	219
4.7.4	Tensioning devices	219
4.7.5	Mechanical mid points	220
4.7.6	Droppers	221
4.7.7	Electrical connections	221
4.7.8	Insulators	221
4.7.9	Sectioning devices	222
4.7.9.1	Type test	222
4.7.9.2	Sample tests	224
4.7.9.3	Routine tests	224
4.7.10	Disconnectors and drives	224
4.7.11	Protection devices	225
4.7.12	Contact line system	225
4.7.12.1	Demonstration of conformity	225
4.7.12.2	Acceptance tests	226
4.7.12.3	Commissioning tests	226
4.8	Systematisation of overhead contact lines and their components	227
4.9	Implemented contact line systems	228
4.9.1	Mass transit systems	228
4.9.2	Main line systems	235

4.9.2.1	Overhead contact lines for DC 3 kV	235
4.9.2.2	Overhead contact lines for DC 1,5 kV	237
4.9.2.3	Overhead contact lines for AC 15 kV 16,7 Hz	238
4.9.2.4	Overhead contact lines for AC 25 kV 50 Hz	246
4.10	References	256
5	Rating overhead contact lines	259
5.1	Assumptions concerning loads and stresses	259
5.1.1	Introduction	259
5.1.2	Dead loads	259
5.1.3	Tensile forces and their components	260
5.1.3.1	Tensile forces acting on conductors and wires	260
5.1.3.2	Components of the tensile forces acting on conductors	264
5.1.3.3	Contact wire wear	268
5.1.4	Wind loads	270
5.1.5	Ice loads	272
5.2	Sag	274
5.2.1	Single trolley-type contact line	274
5.2.1.1	Supports at equal height	274
5.2.1.2	Supports at different heights	277
5.2.1.3	Catenary suspended contact lines	278
5.3	Conductor state change equation	280
5.4	Deflection due to wind	284
5.4.1	Deflection due to wind on tangent track	284
5.4.2	Deflection due to wind and contact wire stagger in curves	285
5.4.2.1	Contact wire offset in still air	285
5.4.2.2	Contact wire offset under wind load	286
5.4.3	Deflection due to wind and contact wire stagger in transition curves	292
5.4.3.1	Basic relations	292
5.4.3.2	Contact wire offset in still air	294
5.4.3.3	Contact wire offset under wind load	295
5.4.4	Deflection of overhead contact line due to wind	298
5.5	Longitudinal span and tensioning section lengths	301
5.5.1	Relevance of span and tension lengths	301
5.5.2	Maximum possible spans	301
5.5.2.1	Significant parameters	301
5.5.2.2	Working range of pantograph head	302
5.5.2.3	Lateral movement of the vehicle	302
5.5.2.4	Contact wire limit position with deflection by wind	303
5.5.2.5	Determination of longitudinal span lengths	305
5.5.3	Determination of tensioning section lengths	308
5.6	References	309

6 Project design	311
6.1 Objective and process	311
6.2 Fundamentals and initial data	314
6.2.1 General	314
6.2.2 Technical requirements and characteristics	314
6.2.3 Planning documents	314
6.2.3.1 Introduction	314
6.2.3.2 Electrification of new lines	317
6.2.3.3 Electrification of existing lines	320
6.2.3.4 Modification of electrified lines	321
6.2.3.5 Tracks and topography	321
6.2.3.6 Circuit diagram	322
6.3 Movement of pantographs	323
6.4 Contact wire height	327
6.5 Contact wire stagger and radial forces	331
6.5.1 Requirements	331
6.5.2 Permissible lateral contact wire displacement	333
6.5.3 Design of contact wire stagger and radial forces	340
6.6 Stagger and height of catenary wires	344
6.7 Determination of span lengths	345
6.8 Tensioning section length	347
6.9 Arrangement of insulated overlapping sections	348
6.10 Contact line above track points	349
6.10.1 Introduction	349
6.10.2 Designation and presentation of track points in drawings	350
6.10.3 Principles of overhead contact lines at track points	353
6.10.4 Arrangement of intersecting wiring at points	354
6.10.4.1 Requirements	354
6.10.4.2 Fitting-free area	356
6.10.4.3 Contact wire height at track points	361
6.10.4.4 Arrangement of crossover droppers at track point areas	363
6.10.4.5 Connection of crossing contact lines at track points	365
6.10.4.6 Definition of lateral position at track points	366
6.10.5 Tangential track point wiring	372
6.11 Route obstacles for wiring	373
6.11.1 General	373
6.11.2 Pole location at track points	373
6.11.3 Signals and signal visibility	376
6.11.4 Crossings of railways by roads and power lines	376
6.11.5 Contact lines under or on engineering structures	377
6.11.6 Example of determination of catenary lowering	385
6.11.7 Location of separations	388
6.11.7.1 Electrical clearances	389
6.11.7.2 Arrangement of phase separation sections	390

6.11.7.3 Arrangement of system separation sections	392
6.11.7.4 Arrangement of pantographs	393
6.12 Layout plan	393
6.12.1 Objective and information	393
6.12.2 Overhead contact line symbols	394
6.12.3 Contact line supports and pole locations	394
6.12.4 Single poles	399
6.12.5 Head-span structures	400
6.12.6 Multiple-track cantilevers	400
6.12.7 Portals	400
6.12.8 Tunnel supports	400
6.12.9 Electrical connections	400
6.12.10 Return current circuits and protective earthing	401
6.12.11 Signals for electric traction	405
6.12.12 Establishing layout plans	405
6.13 Transverse profile diagram	405
6.13.1 Objective and information	405
6.13.2 Types of poles and their classification	405
6.13.3 Pole geometry	407
6.13.4 Transverse switching lines, disconnectors on poles	407
6.13.5 Determination of pole lengths	409
6.13.6 Cantilevers	411
6.13.7 Pole and foundation selection	412
6.13.8 Head-span structures	413
6.13.9 Portals	416
6.14 Longitudinal profiles	418
6.14.1 Contents	418
6.14.2 Dropper arrangement	418
6.14.3 Contact line height reductions	419
6.14.4 Traction power line longitudinal profile	419
6.14.5 Minimum clearances to overhead lines and traction feeder lines	420
6.14.5.1 Introduction	420
6.14.5.2 Protection by clearance	422
6.14.5.3 Protection by obstacles or barriers	424
6.14.6 Traction power lines	428
6.14.6.1 Definitions and requirements	428
6.14.6.2 Line attachment to poles	428
6.14.6.3 Clearance verification	429
6.15 Project documentation	434
6.16 Computer supported planning	436
6.16.1 Objectives	436
6.16.2 Structure and modules	436
6.16.3 Project management module	437
6.16.4 Process data module	437

6.16.5	Track layout module	437
6.16.6	Contact overhead contact line design module	440
6.16.7	Output and export module	440
6.16.8	Hardware and software	441
6.16.9	Application	441
6.17	References	442
7	Cross-span structures, poles and foundations	445
7.1	Loads and other actions on contact lines	445
7.1.1	Introduction	445
7.1.2	Classification of actions	445
7.1.3	Permanent actions	446
7.1.4	Variable actions	446
7.1.4.1	General	446
7.1.4.2	Wind loads	447
7.1.4.3	Ice loads	450
7.1.4.4	Combined action of wind and ice	451
7.1.4.5	Temperature effects	451
7.1.5	Loads due to construction, maintenance and other conditions	452
7.2	Transverse support and registration	452
7.2.1	Types of transverse support equipment	452
7.2.2	Swivel cantilevers	452
7.2.3	Cantilever across several tracks	453
7.2.4	Flexible transverse support equipment	454
7.2.5	Portal structures	454
7.3	Poles	455
7.3.1	Types of poles	455
7.3.2	Loading assumptions	456
7.3.3	Partial factors for actions	458
7.3.4	Structural design and materials	458
7.4	Rating of cross-span supports	461
7.4.1	Introduction	461
7.4.2	Cantilevers	461
7.4.2.1	Loading and internal forces and moments	461
7.4.2.2	Rating based on EN 50 119	463
7.4.3	Flexible cross-supporting structures	467
7.4.3.1	Introduction	467
7.4.3.2	Loading, internal forces and sag of head span wires	467
7.4.3.3	Determination of head-span pole lengths	469
7.4.3.4	Loading and internal forces of cross-span wires	470
7.4.3.5	Rating of head-span wires and cross-span wires	471
7.4.4	Horizontal registration arrangements	471
7.5	Rating of poles	473
7.5.1	Introduction	473

7.5.2	Determination of pole length	473
7.5.3	Loadings and internal forces and moments	474
7.5.4	Rating of structural components	476
7.5.4.1	Introduction	476
7.5.4.2	Lattice steel poles	476
7.5.4.3	Double channel poles	480
7.5.4.4	H-beam poles	481
7.5.4.5	Steel reinforced concrete poles	482
7.5.4.6	Deflection	485
7.6	Subsoil	487
7.6.1	Introduction	487
7.6.2	Undisturbed soil	488
7.6.2.1	Classification	488
7.6.2.2	Non-cohesive, granular	488
7.6.2.3	Cohesive soils	489
7.6.2.4	Composite soils	489
7.6.2.5	Organic soils	489
7.6.3	Rock	490
7.6.4	Soil fill	490
7.6.5	Soil investigation	490
7.6.6	Methods of obtaining soil samples	490
7.6.6.1	Introduction	490
7.6.6.2	Investigation by boring	491
7.6.6.3	Investigation by probes	491
7.6.7	Probing	492
7.6.7.1	Introduction	492
7.6.7.2	Driven probes in accordance with EN ISO 22476-2	492
7.6.7.3	Standard Penetration Test	492
7.6.8	Evaluation of soil investigation	493
7.6.9	Soil characteristics	493
7.6.10	Practical application	494
7.7	Foundations	497
7.7.1	Basis of design	497
7.7.2	Concrete block foundations with side-bearing faces	498
7.7.3	Block foundations with steps	502
7.7.4	Driven pile foundations	506
7.7.5	Anchor foundations	510
7.8	Example	512
7.8.1	Contact line data	512
7.8.2	Loads	513
7.8.3	Design of pole	514
7.8.4	Cantilever	515
7.8.5	Foundation	518
7.9	References	520

8 Designs for special applications	521
8.1 Introduction	521
8.2 Maintenance installations	521
8.3 Avoidance and removal of ice on contact lines	524
8.3.1 Introduction	524
8.3.2 Mechanical techniques	525
8.3.3 Chemical techniques	525
8.3.4 Electrical techniques	526
8.3.5 Combined techniques	531
8.4 Tunnel seals	531
8.5 Interface between electrification systems	532
8.5.1 Introduction and requirements	532
8.5.2 System separation sections on interstation lines	533
8.5.3 Stations with two power supply systems	536
8.5.4 Operating AC and DC trains on the same track	538
8.6 Movable bridges	538
8.6.1 Application and electrification	538
8.6.2 Contact line design	539
8.6.2.1 Folding bridges	539
8.6.2.2 Swivelling bridges	540
8.6.2.3 Lifting bridges	543
8.6.3 Electrical connections and signalling	545
8.7 Level crossings of lines fed by differing power supply systems	546
8.7.1 Crossing between mainline railways and tramways	546
8.7.2 Crossings between light-rail and trolley bus lines	548
8.8 Contact line design above road level crossings	551
8.8.1 Arrangements for standard-height road transports	551
8.8.2 Arrangements for oversize transports with permanently increased contact wire heights	552
8.8.3 Arrangement of gaps within the overhead contact line	552
8.8.4 Temporary lifting of contact line by movable cantilevers	553
8.8.5 Temporary lifting or removing of the contact lines by manual procedures	555
8.9 Container terminals, loading and checking tracks, railway lines in mines	556
8.9.1 Swivelling contact lines	556
8.9.2 Circuit diagrams for loading and checking tracks	557
8.9.3 Movable stopes and laterally arranged overhead contact lines	560
8.10 References	560
9 Interaction of pantograph and overhead contact line	563
9.1 Introduction	563
9.2 Basic principles	563
9.2.1 Pantograph running along an overhead contact line	563

9.2.2	Contact wire subjected to a moving pantograph exerting a constant force	565
9.2.3	Contact wire uplift at high speeds	567
9.2.4	Reflection of transversal impulses travelling along a contact wire at a concentrated mass.	569
9.2.5	Reflection of transversal impulses at a dropper	572
9.2.6	Doppler factor	574
9.2.7	Natural frequencies of an overhead contact line	576
9.2.8	Dynamic characteristics of typical overhead contact line designs	576
9.3	Simulation of pantograph overhead contact line interaction	578
9.3.1	Objectives	578
9.3.2	Model of the pantograph system	579
9.3.3	Contact line models	582
9.3.3.1	Basic considerations	582
9.3.3.2	Modelling with the aid of the finite-element method	583
9.3.3.3	Analytical solution in the frequency area	583
9.3.3.4	Method using frequency-dependent finite elements	584
9.3.3.5	Modelling on the basis of d’Alambert’s wave equations	584
9.3.4	Validation of simulation methods	584
9.3.4.1	Introduction	584
9.3.4.2	Requirements on simulation methods	586
9.3.4.3	Validation by comparison with the reference model	587
9.3.4.4	Validation with measured values	588
9.3.5	Interaction simulation using frequency-dependent finite elements	588
9.3.6	Simulation with commercially available finite element programs	592
9.3.7	Simulation with a program tailored to overhead contact lines	595
9.4	Measurements and tests	597
9.4.1	Introduction	597
9.4.2	Requirements on the interaction between overhead contact lines and pantographs	600
9.4.2.1	Introduction	600
9.4.2.2	Static contact force	600
9.4.2.3	Mean contact force	600
9.4.2.4	Requirements for dynamic behaviour and quality of current collection	602
9.4.2.5	Vertical movement of the contact point	603
9.4.2.6	Requirements on conformity assessment interoperability constituent overhead contact line	603
9.4.3	Measurements of the interaction between overhead contact lines and pantographs	605
9.4.3.1	Basic principles	605
9.4.3.2	Requirements on interaction measurements	606
9.4.3.3	Description of DB’s contact force measuring technologies	608
9.4.3.4	Measured quantities	612

9.4.3.5	Effects due to aerodynamic uplift force acting on the collector strips	615
9.4.3.6	Evaluation and assessment of the measurement results	616
9.4.4	Measurement of overhead contact line position and of contact wire thickness	620
9.4.5	Assessment of dynamic characteristics of pantographs	622
9.4.6	Measurement of contact wire uplift and dynamic contact line elasticity	624
9.4.6.1	Stationary measurement of contact wire uplift	624
9.4.6.2	Mobile measurement of the contact wire uplift	626
9.4.6.3	Measurement of the dynamic elasticity	626
9.5	Effects of contact line design	627
9.5.1	Introduction	627
9.5.2	Criteria for overhead contact line designs	627
9.5.2.1	Elasticity and uplift	627
9.5.2.2	Dynamic criteria	630
9.5.3	Overhead contact line design parameters	632
9.5.3.1	Cross-sectional areas and tensile stress	632
9.5.3.2	Span lengths and system height	634
9.5.3.3	Pre-sag and stitch wires	636
9.5.3.4	Effect of adjustment accuracy	638
9.6	Effects of pantograph design	639
9.6.1	Introduction	639
9.6.2	Features of pantograph designs	639
9.6.3	Sophisticated pantograph design	642
9.6.4	Trains running with multiple pantographs	643
9.7	Collector strip and contact wire materials	645
9.8	Conclusions	649
9.8.1	Limits for the transmission of energy via overhead contact lines and pantographs	649
9.8.2	Overhead contact line requirements	652
9.8.3	Pantograph requirements	653
9.8.4	Requirements concerning the interaction of overhead contact lines and pantographs	655
9.9	References	656
10	Currents and voltages	661
10.1	Electrical characteristics of contact lines	661
10.1.1	Basic relationships	661
10.1.2	Impedances	662
10.1.2.1	Components	662
10.1.2.2	Resistance per unit length	663
10.1.2.3	Inductance, reactance and impedance	665
10.1.2.4	Impedance of running rails	668
10.1.2.5	Impedance of AC overhead contact lines	668

10.1.2.6	Measuring the impedances of contact lines	671
10.1.2.7	Calculated and measured impedances per unit length	677
10.1.3	Capacitances per unit length	677
10.2	Voltages in contact line networks	679
10.2.1	Basic requirements and principles	679
10.2.2	Voltage drop calculations	681
10.2.2.1	Introduction	681
10.2.2.2	Single-end feed	681
10.2.2.3	Double-end feed	683
10.2.3	Other calculation algorithms	686
10.2.4	Mean useful voltage	688
10.2.4.1	Requirements and definitions	688
10.2.4.2	Calculation	689
10.3	Electric traction loads	690
10.3.1	Introduction	690
10.3.2	Time-weighted equivalent continuous load	691
10.3.3	Railways for general traffic	693
10.3.4	Power factor	700
10.3.5	High-speed and heavy-duty railway lines	700
10.3.6	Maximum train currents	701
10.3.7	Short-circuit loads	702
10.4	Line feeding circuits	706
10.4.1	Basic requirements for line feeding circuits	706
10.4.2	Basic types of circuits	707
10.4.3	Overhead contact line circuits of 16,7 Hz railways	709
10.4.3.1	Development	709
10.4.3.2	Contact line circuits used by the German railways, DB	710
10.4.3.3	Codes used in circuit diagrams	713
10.4.3.4	Contact line circuits of European 16,7 Hz railways	714
10.5	References	717
11	Current-carrying capacity and protective provisions	721
11.1	Current-carrying capacity	721
11.1.1	Introduction	721
11.1.2	Single conductors	721
11.1.2.1	Basic relations	721
11.1.2.2	Long-term operational loads	722
11.1.2.3	Short-circuit current-carrying capacity	729
11.1.2.4	Varying operational loads	733
11.1.2.5	Conductor rails	734
11.1.3	Overhead contact lines	736
11.1.4	Thermal design calculations	739
11.1.4.1	Maximum principle	739
11.1.4.2	Matching load and current-carrying capacity characteristics	740

11.2 Effects of temperature on contact wire characteristics	742
11.2.1 Introduction	742
11.2.2 Characteristics of contact wire material	743
11.2.3 Effect of heating on the tensile strength	745
11.2.4 Effect of exposure period to increased temperatures on the tensile strength	747
11.2.5 Heating and reduction of contact wire tensile strength at locations subject to increased wear and at connection terminals	748
11.2.6 Interface between contact wire and collector strips	750
11.3 Line protection and fault location	753
11.3.1 Purpose and requirements of protective provisions for contact line systems	753
11.3.2 Components and design	755
11.3.2.1 Overview	755
11.3.2.2 High-current and overcurrent time protection stages	756
11.3.2.3 Distance protection	757
11.3.2.4 Starting stage	757
11.3.2.5 Overload protection	758
11.3.2.6 Other components in digital protection equipment	759
11.3.2.7 Protection settings	760
11.3.3 Fault localization	766
11.4 References	767
12 Current return circuit and earthing	771
12.1 Introduction	771
12.2 Terms and Definitions	772
12.2.1 Introduction	772
12.2.2 Earth	772
12.2.3 Earth electrode	773
12.2.4 Soil resistivity and resistance to earth	773
12.2.5 Structure earth, tunnel earth	773
12.2.6 Rail potential and track-to-earth voltage	773
12.2.7 Touch voltage	773
12.2.8 Accessible voltage	774
12.2.9 Overhead contact line zone and pantograph zone	774
12.2.10 Return circuit	774
12.2.11 Stray Current	775
12.3 Design principles and requirements	775
12.3.1 Principles of AC and DC railways	775
12.3.2 Return circuit of DC railways	776
12.3.3 Return circuit of AC railways	777
12.3.4 Protection against electric shock, safety	777
12.3.5 Permissible touch voltages	779
12.3.6 Interference	782

12.3.7 Stray current corrosion	783
12.3.8 Measurements	783
12.4 Return currents and rail potentials	784
12.4.1 Soil resistivity and conductivity	784
12.4.2 Earth electrodes in the vicinity of railways	785
12.4.2.1 Earth resistance of electrodes and pole earthing	785
12.4.2.2 Effective conductance between tracks and earth	787
12.4.3 Track-to-earth circuit	791
12.4.3.1 General	791
12.4.3.2 Track-earth circuit of DC systems	791
12.4.3.3 Track-to-earth circuit of AC systems	793
12.4.4 Rail potentials	798
12.4.4.1 AC systems	798
12.4.4.2 DC systems	800
12.4.4.3 Rail potential under operational conditions	800
12.4.4.4 Track-to-earth voltage in case of short-circuits	801
12.5 Direct-current traction systems	803
12.5.1 Design of the return circuit and earthing installations	803
12.5.2 Safety of persons	804
12.5.3 Stray current protection	805
12.5.3.1 General information	805
12.5.3.2 Voltage and current distribution	807
12.5.3.3 Effect of the polarity	809
12.5.3.4 Protective measures against stray current corrosion	810
12.5.3.5 Stray current collecting nets	812
12.5.4 Design of DC installations with respect to return circuit and earthing	813
12.5.4.1 Basic recommendations	813
12.5.4.2 Railway-owned earthing systems	814
12.5.4.3 Three-phase power supply	814
12.5.4.4 Traction substations	815
12.5.4.5 At-grade line sections	815
12.5.4.6 Passenger stations	816
12.5.4.7 Signalling and telecommunications installations	816
12.5.4.8 Depot and workshop areas	817
12.5.4.9 Tunnels	818
12.5.4.10 Lightning protection	820
12.5.4.11 Third party earthing installations	821
12.5.4.12 Implementation of electrification projects	821
12.5.4.13 Verification measurements	822
12.5.5 Earthing and bonding for Ankaray LRT system	822
12.5.5.1 Description of the project	822
12.5.5.2 Measurement of the resistance to earth	822
12.5.5.3 Measurement of rail potentials	822
12.5.5.4 Measurement of rail insulation	822

12.5.5.5	Measurement of the potential between structure earth and reference earth	823
12.5.5.6	Current through voltage limiting devices in the stations	823
12.5.6	Maintenance	823
12.5.7	Conclusions for DC return circuit and earthing	824
12.6	Alternating current traction systems	825
12.6.1	Design requirements	825
12.6.1.1	General	825
12.6.1.2	Safety of persons	826
12.6.1.3	Limitation of interference	828
12.6.2	Characteristics of current return systems	828
12.6.2.1	Current return through rails and earth-buried return conductors	828
12.6.2.2	Return conductors	829
12.6.2.3	Auto-transformers	831
12.6.2.4	Booster transformers	832
12.6.3	Design of current return and earthing installations	833
12.6.3.1	Basic requirements	833
12.6.3.2	Substations and stations	835
12.6.3.3	At-grade line sections	835
12.6.3.4	Tunnel sections	836
12.6.3.5	Viaducts	837
12.6.3.6	Depot and workshop areas	838
12.6.3.7	Signalling and telecommunications installations	838
12.6.3.8	Third-party earthing installations	838
12.6.3.9	Lightning protection	839
12.6.3.10	Implementation	840
12.6.3.11	Verification measurements	840
12.6.4	Earthing and bonding for DB lines	841
12.6.4.1	Design of traction current return circuits	841
12.6.4.2	Track with uninsulated rails	842
12.6.4.3	Track with single-rail insulation	842
12.6.4.4	Track with both rails insulated	842
12.6.4.5	Track with audio-frequency circuits	843
12.6.4.6	Cabling requirements for bonds	844
12.6.4.7	Crossbonding between the return circuit and steel reinforcement of concrete structures	844
12.6.5	Earthing and bonding of the Madrid-Seville AC 25 kV 50 Hz high-speed line	845
12.6.6	Conclusion for design of AC return circuit and earthing	848
12.7	References	848
13	Interferences	853
13.1	Introduction	853
13.2	Interferences due to electric traction systems	853

13.3 Coupling mechanisms	854
13.3.1 General	854
13.3.2 Galvanic interference	856
13.3.3 Inductive interference	856
13.3.3.1 Inductive interference related to the power frequency	856
13.3.3.2 Inductive interference related to harmonics	861
13.3.4 Capacitive interference	864
13.4 Electric and magnetic fields in the vicinity of traction contact lines	865
13.4.1 Basics	865
13.4.2 Effects on human beings	867
13.4.3 Effects of fields on equipment	869
13.4.3.1 Effects in general	869
13.4.3.2 Persons with implanted cardiac pacemakers	869
13.4.3.3 Information technology and electronic data processing equipment . .	870
13.4.3.4 Electric railways as sources of radio-frequency interference	870
13.5 Conclusions	871
13.6 References	873
14 Construction, management and maintenance	875
14.1 Introduction	875
14.2 Construction	875
14.2.1 Principles	875
14.2.2 Production of components	876
14.2.3 Installation and assembly work	876
14.2.3.1 Introduction	876
14.2.3.2 Foundation and pole setting work	878
14.2.3.3 Installation and adjustment of the overhead line supports and contact lines	878
14.2.3.4 High-speed contact line installation	881
14.2.3.5 Installation of section insulators, cross-over contact lines, traction power supply lines and railway earthing	884
14.2.4 Acceptance and commissioning	886
14.2.4.1 General	886
14.2.4.2 Preparation of the acceptance procedure	886
14.2.4.3 Acceptance of contact lines for conventional lines	886
14.2.4.4 Acceptance of contact lines of interoperable high-speed lines . . .	887
14.2.4.5 Documents and responsibilities for interoperable high-speed lines .	888
14.3 Management	890
14.3.1 Training and instruction of staff	890
14.3.2 Electrotechnical conduct standards and service guidelines	891
14.3.3 Switching and earthing	892
14.3.4 Special installations for overhead contact line earthing in tunnels . . .	894
14.3.4.1 General	894
14.3.4.2 Emergency overhead contact line earthing in tunnels in Germany .	894

14.3.4.3 Emergency earthing in tunnels in the Netherlands	894
14.3.5 Irregularities and their recognition	897
14.4 Wear and ageing	897
14.4.1 Classification of components	897
14.4.2 Concrete poles and foundations	898
14.4.3 Steel poles, cantilevers and other support structures	899
14.4.4 Traction power supply lines, messenger wires, droppers and connectors	900
14.4.5 Contact Wires	901
14.4.6 Insulators	905
14.4.7 Disconnectors and section insulators	906
14.5 Maintenance	907
14.5.1 Scope of maintenance	907
14.5.2 Reliability	908
14.5.3 Diagnostics	912
14.5.4 Statistical recording and analysis of faults	916
14.5.5 Corrective maintenance	918
14.6 Recycling and disposal	919
14.6.1 Dismantling	919
14.6.2 Suitable preparation and disposal of materials for recycling	920
14.7 Equipment for installation and maintenance	920
14.7.1 Tools and equipment	920
14.7.2 Specialist vehicles	922
14.7.3 Measuring and diagnostic equipment	930
14.7.3.1 General	930
14.7.3.2 Contact wire geometrical position measurements	930
14.7.3.3 Optical contactless inspection	934
14.7.3.4 Measurement of inclinations	937
14.7.3.5 Measurement of wire tensile forces	938
14.7.3.6 Uplift measurement	938
14.7.3.7 Contact line monitoring	940
14.7.3.8 Contact wire wind deflection measurement	943
14.7.3.9 Pantograph monitoring system	945
14.7.3.10 Monitoring of the rail potential in DC traction systems	945
14.7.3.11 Temperature measurement	947
14.7.3.12 Thermovision measuring	947
14.7.3.13 Contact force measurement	948
14.8 Life cycle considerations	949
14.9 References	951
Appendix 1: Standards and regulations	955
Appendix 2: Frequently used abbreviations	965